The $B \to X_s l^+ l^-$ and $B \to X_s \gamma$ decays with the fourth generation

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Abstract

If the fourth generation fermions exist, the new quarks could influence the branching ratios of the decays of $B \to X_s\gamma$ and $B \to X_s l^+ l^-$. We obtain two solutions of the fourth generation CKM factor $V_{t's}^* V_{t'b}$ from the decay of $B \to X_s\gamma$. We use these two solutions to calculate the new contributions of the fourth generation quark to Wilson coefficients of the decay of $B \to X_s l^+ l^-$. The branching ratio and the forward-backward asymmetry of the decay of $B \to X_s l^+ l^-$ in the two cases are calculated. Our results are quite different from that of SM in one case, almost same in another case. If Nature chooses the formmer, the B meson decays could provide a possible test of the forth generation existence.

1   Introduction

The standard model (SM) is very successful. But it is almost certainly incomplete. For example, it does not fix the number of generations. So far it is not known why there is more than one generation and what law of Nature determines their number. The LEP determinations of the invisible partial decay width of the Z^0 gauge boson show there are certainly three light neutrinos of the usual type with mass than $M_Z/2$ [1]. This result is naturally interpreted to imply that there are exactly three generations of quarks and leptons. However, the existence of the fourth generation is not excluded, if the neutrino of this generation is, for unknown reasons, heavy, i. e., $m_{\nu_4} \geq M_Z/2$ [2]. That is, there still exists the room of the fourth generation.

If we believe that the fourth generation fermions really exist in Nature, we should give their mass spectrums and take into account their physical effects. In last two decades, many theorists have researched this question. For examples, refs.[3] researched the mass spectrum of the fourth generation fermions in the minimal SUSY model and the supergravity model respectlivily. Refs. [4] considered only the fourth generation neutrino. Refs.

[5] discussed the limit on the masses of the fourth generation neutral and charged leptons, $m_{\nu'}$ and $m_{\tau'}$, which had been improved by LEP1.5 to $m_{\nu'} > 59\text{GeV}$ and $m_{\tau'} > 62\text{GeV}$. Ref. [6] reported on a search for pair production of a fourth generation charge $-1/3$ quark b' in $p\bar{p}$ collisions at $\sqrt{s} = 1.8\text{TeV}$ by the DØ experiment at the Fermilab Tevatron using an integrated luminosity of 93pb^{-1}. There were also many papers presented other problems about the fourth generation, such as the mass degenercy of the fourth generation [7], the vector-like doublet as the fourth generation [8], and so on [9]. Recently, it is noted that the S parmeter measured from precision electroweak data is in conflict with a degenerate fourth generation by over three standard deviations, or 99.8% [10]. However, one can get around this discrepancy by assuming that there is new physics which partially cancels the contribution of fourth generation to the S parameter (such as additional Higgs doublets, etc.). On the other hand, it is shown that the area of mutual inconsistency between the SM and MSSM Higgs mass bounds is found to be consistent with the four generation MSSM upper bounds [11]. Ref. [12] examined the motivation of the existence of generation by operator ordering ambiguity and found that there should be four generations. It has been pointed that the fourth generation fermions would increase the Higgs boson production cross section via gluon fusion at hadron collider [13]. The decays of the fourth generation fermions have also been investigated [14]. The introduction of fourth generation fermions can also affect CP violating parameters ϵ'/ϵ in the kaon system[15].

There were several theoretical schemes to introduce the fourth generation in the SM. The most economical and simple one was considered in Ref. [3]. The fourth generation model in this note is similar to that. But we limit ourself to the non-SUSY case in order to concentrate on the phenomenological implication of the fourth generation. We introduce the fourth generation, an up-like quark t', a down-like quark b', a lepton τ', and a heavy neutrino ν' in the SM. The properties of these new fermions are all the same as their corresponding counterparts of other three generations except their masses and CKM mixing, see tab.1,

	up-like quark	down-like quark	charged lepton	neutral lepton
SM fermions	u	d	e	ν_e
	c	s	μ	ν_μ
	t	b	τ	ν_τ
new fermions	t'	b'	τ'	$\nu_{\tau'}$

Table 1: The elmentary particle spectrum of SM4

In this note, we investigate the inclusive decays of $B \to X_s l^+ l^-$ and $B \to X_s \gamma$ in the four generation SM which we shall call SM4 hereafter for the sake of simplicity. These two rare B meson decays provide testing grounds for the SM and are very useful for constraining new physics beyond the SM [16, 17]. They are experimentally clean, and are sensitive to the various extensions to the SM because these decays occur only through loops in the SM. New physical effects can manifest themselves in these rare decays through the Wilson coefficients, which can have values distinctly different from their SM counterparts

[18, 19, 20, 21], as well as new operators [20]. The implication of a fourth generation of quarks on the process $b \to s$ have previously investigated [21, 22] and it is shown that the fourth generation $b \to s\gamma$ branching ratio is essentially within the range allowed by CLEO [22].

The fourth generation quarks would influence these two decays. We obtain two solutions of the fourth generation CKM factor $V_{t's}^* V_{t'b}$ from the decay of $B \to X_s\gamma$. Then we use these two solutions to calculate the new contributions of the fourth generation quark to Wilson coefficients of the decay of $B \to X_s l^+ l^-$. The branching ratio and the forward-backward asymmetry of the decay of $B \to X_s l^+ l^-$ in the two cases are calculated. Our results are quite different from that of SM in one case, almost same in another case. If Nature chooses the formmer, the B meson decays could provide a possible test for the existence of the fourth generation fermions.

2 The decay of $B \to X_s\gamma$ and the fourth generation CKM factor $V_{t's}^* V_{t'b}$

The rare decay $B \to X_s\gamma$ plays an important role in present day phenomenology. The effective Hamiltonian for $B \to X_s\gamma$ at scales $\mu_b = \mathcal{O}(m_b)$ is given by [17, 23]

$$\mathcal{H}_{\text{eff}}(b \to s\gamma) = -\frac{G_{\text{F}}}{\sqrt{2}} V_{ts}^* V_{tb} \left[\sum_{i=1}^{6} C_i(\mu_b) Q_i + C_{7\gamma}(\mu_b) Q_{7\gamma} + C_{8G}(\mu_b) Q_{8G} \right], \tag{1}$$

The last two operators in the eq.(1), characteristic for this decay, are the magnetic–penguin operators

$$Q_{7\gamma} = \frac{e}{8\pi^2} m_b \bar{s}_\alpha \sigma^{\mu\nu} (1 + \gamma_5) b_\alpha F_{\mu\nu}, \qquad Q_{8G} = \frac{g}{8\pi^2} m_b \bar{s}_\alpha \sigma^{\mu\nu} (1 + \gamma_5) T_{\alpha\beta}^a b_\beta G_{\mu\nu}^a \tag{2}$$

The leading logarithmic calculations can be summarized in a compact form as follows [17]:

$$R_{\text{quark}} = \frac{Br(B \to X_s\gamma)}{Br(B \to X_c e\bar{\nu}_e)} = \frac{|V_{ts}^* V_{tb}|^2}{|V_{cb}|^2} \frac{6\alpha}{\pi f(z)} |C_7^{\text{eff}}(\mu_b)|^2, \tag{3}$$

where

$$f(z) = 1 - 8z + 8z^3 - z^4 - 12z^2 \ln z \quad \text{with} \quad z = \frac{m_{c,pole}^2}{m_{b,pole}^2} \tag{4}$$

is the phase space factor in $Br(B \to X_c e\bar{\nu}_e)$ and $\alpha = e^2/4\pi$. The coefficient $C_7^{\text{eff}}(\mu_b)$ can be calculated by using the renormalization group equations and the values of the Wilson coefficients $C_{7\gamma}$ and C_{8G} at the scale $\mu_W = O(m_W)$, $C_{7\gamma}(\mu_W)$ and $C_{8G}(\mu_W)$, which in SM are given in Ref. [24].

In the case of four generation there is an additional contribution to $B \to X_s\gamma$ from the virtual exchange of the fourth generation up quark t'. The Wilson coefficients of the
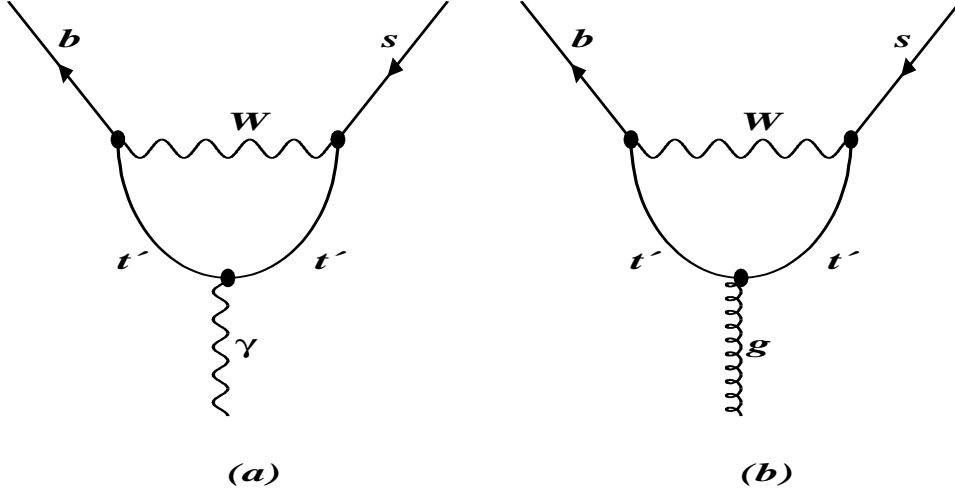
Figure 1: Mabnetic Photon (a) and Gluon (b) Penguins with t'.

dipole operators are given by

$$C_{7,8}^{\text{eff}}(\mu_b) = C_{7,8}^{(\text{SM})\text{eff}}(\mu_b) + \frac{V_{t's}^* V_{t'b}}{V_{ts}^* V_{tb}} C_{7,8}^{(4)\text{eff}}(\mu_b), \tag{5}$$

where $C_{7,8}^{(4)\text{eff}}(\mu_b)$ present the contributions of t' to the Wilson coefficients, and $V_{t's}^*$ and $V_{t'b}$ are two elements of the 4×4 CKM matrix which now contains nine paremeters, i.e., six angles and three phases. We recall here that the CKM coefficient corresponding to the t quark contribution, i.e., $V_{ts}^* V_{tb}$, is factorized in the effective Hamiltonian as given in Eq. (1). The formulas for calculating the Wilson coefficients $C_{7,8}^{(4)}(m_W)$ are same as their counterpaters in the SM except exchanging t' quark not t quark and the corresponding Fenymann figuers are shown in fig. 1.

With these Wilson coefficients and the experiment results of the decays of $B \to X_s \gamma$ and $Br(B \to X_c e \bar{\nu}_e)$ [25, 26], we obtain the results of the fourth generation CKM factor $V_{t's}^* V_{t'b}$. There exist two cases, a positive factor and a negative one:

$$V_{t's}^* V_{t'b}^{(+)} = [C_7^{(0)\text{eff}}(\mu_b) - C_7^{(\text{SM})\text{eff}}(\mu_b)] \frac{V_{ts}^* V_{tb}}{C_7^{(4)\text{eff}}(\mu_b)}$$

$$= [\sqrt{\frac{R_{\text{quark}} |V_{cb}|^2 \pi f(z)}{|V_{ts}^* V_{tb}|^2 6\alpha}} - C_7^{(\text{SM})\text{eff}}(\mu_b)] \frac{V_{ts}^* V_{tb}}{C_7^{(4)\text{eff}}(\mu_b)} \tag{6}$$

$$V_{t's}^* V_{t'b}^{(-)} = [-\sqrt{\frac{R_{\text{quark}} |V_{cb}|^2 \pi f(z)}{|V_{ts}^* V_{tb}|^2 6\alpha}} - C_7^{(\text{SM})\text{eff}}(\mu_b)] \frac{V_{ts}^* V_{tb}}{C_7^{(4)\text{eff}}(\mu_b)} \tag{7}$$

4

$m_{t'}$ (Gev)	50	100	150	200	250	300	400
$V_{t's}^* V_{t'b}^{(+)} \times 10^{-2}$	-11.591	-9.259	-8.126	-7.501	-7.116	-6.861	-6.548
$V_{t's}^* V_{t'b}^{(-)} \times 10^{-3}$	3.5684	2.8503	2.5016	2.3092	2.191	2.113	2.016

Table 2: The values of $V_{t's}^* \cdot V_{t'b}$ due to masses of t' for $Br(B \to X_s\gamma) = 2.66 \times 10^{-4}$

as in tab. 2,

In the numerical calculations we set $\mu_b = m_b = 5.0GeV$ and take the t' mass value of 50GeV, 100GeV, 150GeV, 200GeV, 250GeV, 300GeV, 400 Gev [3].

The CKM matrix elements obey unitarity constraints, which states that any pair of rows, or any pair of columns, of the CKM matrix are orthogonal. This leads to six orthogonality conditions [16]. The one relevant to $b \to s\gamma$ is

$$\sum_i V_{is}^* V_{ib} = 0, \tag{8}$$

i.e.,

$$V_{us}^* V_{ub} + V_{cs}^* V_{cb} + V_{ts}^* V_{tb} + V_{t's}^* V_{t'b} = 0. \tag{9}$$

We take the average values of the SM CKM matrix elements from Ref. [26]. The sum of the first three terms in eq. (9) is about 7.6×10^{-2}. If we take the value of $V_{t's}^* V_{t'b}^{(+)}$ given in Table 2, the result of the left of (9) is much better and much more close to 0 than that in SM, because the value of $V_{t's}^* V_{t'b}^{(+)}$ is very close to the sum but has the opposite sign. If we take $V_{t's}^* V_{t'b}^{(-)}$, the result would change little because the values of $V_{t's}^* V_{t'b}^{(-)}$ are about 10^{-3} order, ten times smaller than the sum of the first three ones in the left of (9). Considering that the data of CKM matrix is not very accurate, we can get the error range of the sum of these first three terms. It is about $\pm 0.6 \times 10^{-2}$, much larger than $V_{t's}^* V_{t'b}^{(-)}$. Thus, the values of $V_{t's}^* V_{t'b}$ in the both cases satisfy the CKM matrix unitarity constraints.

3   The decay of $B \to X_s l^+ l^-$

The effective hamiltonian of the decay of $B \to X_s l^+ l^-$ is

$$H_{eff} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} C_i(\mu) O_i(\mu) \tag{10}$$

where O_i are given in Refs. [17, 27]. The formulas for calculating the coefficients $C_i(m_W)$ in SM can be found in [17, 27]. Similar to Eq. (5), the Wilson coefficients C_9 and C_{10} which, in addition to C_7, are responsible for the decay $B \to X_s l^+ l^-$ can be written in SM4 as

$$C_9(\mu_b) = C_9^{(SM)}(\mu_b) + \frac{V_{t's}^* V_{t'b}}{V_{ts}^* V_{tb}} C_9^{(4)}(\mu_b) \tag{11}$$

5

$$C_{10}(\mu_b) = C_{10}^{(SM)}(\mu_b) + \frac{V_{t's}^* V_{t'b}}{V_{ts}^* V_{tb}} C_{10}^{(4)}(\mu_b), \tag{12}$$

where $C_{9,10}^{(4)}$, the contribution of t' to the Wilson coefficient $C_{9,10}$, is easily obtained by using the expression in SM with substituting m_t for $m_{t'}$.

The effective Hamiltonian results in the following matrix elements for $B \to X_s l^+ l^-$

$$
\begin{aligned}
M &= \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* [C_9^{eff} \bar{s}_L \gamma_\mu b_L \bar{l} \gamma^\mu l + C_{10} \bar{S}_L \gamma_\mu b_L \bar{l} \gamma^\mu \gamma^5 l \\
&\quad + 2C_7 m_b \bar{s}_L i\sigma^{\mu\nu} \frac{q^\mu}{q^2} b_R \bar{l} \gamma^\nu l],
\end{aligned}
\tag{13}
$$

here these coefficients are evaluated at $\mu = m_b$. C_9^{eff} is given as[27]:

$$C_9^{eff} = C_9 + [g(\frac{m_c}{m_b}, s) + \frac{3}{\alpha^2} k \sum_{V_i} \frac{\pi M_{V_i} \Gamma(V_i \to l^+ l^-)}{M_{V_i}^2 - q^2 - i M_{V_i} \Gamma_{V_i}}](3C_1 + C_2) \tag{14}$$

From eq.(13), by integrating the angle variable of the double differential distributions from 0 to π, the invariant dilepton mass distributions can be calculated and given below

$$
\begin{aligned}
\frac{d\Gamma(B \to X_s l^+ l^-)}{ds} &= B(B \to X_c l\bar{\nu}) \frac{\alpha^2}{4\pi^2 f(m_c/m_b)} (1-s)^2 (1 - \frac{4t^2}{s})^{1/2} \frac{|V_{tb} V_{ts}^*|^2}{|V_{cb}|^2} D(s), \\
D(s) &= |C_9^{eff}|^2 (1 + \frac{2t^2}{s})(1 + 2s) + 4|C_7|^2 (1 + \frac{2t^2}{s})(1 + \frac{2}{s}) \\
&\quad + |C_{10}|^2 [(1 + 2s) + \frac{2t^2}{s}(1 - 4s)] + 12\mathrm{Re}(C_7 C_9^{eff*})(1 + \frac{2t^2}{s}) \quad (15)
\end{aligned}
$$

where $s = q^2/m_b^2$, $t = m_l/m_b$, $B(B \to X_c l\bar{\nu})$ is the branching ratio which takes as 0.11, f is the phase-space factor expressed in eq.(4). The forward-backward asymmetry of the lepton in the process has also been given

$$
\begin{aligned}
A(s) &= -3(\frac{1 - 4t^2}{s})^{1/2} E(s)/D(s) \\
E(s) &= \mathrm{Re}(C_9^{eff} C_{10}^*)s + 2\mathrm{Re}(C_7 C_{10}^*)
\end{aligned}
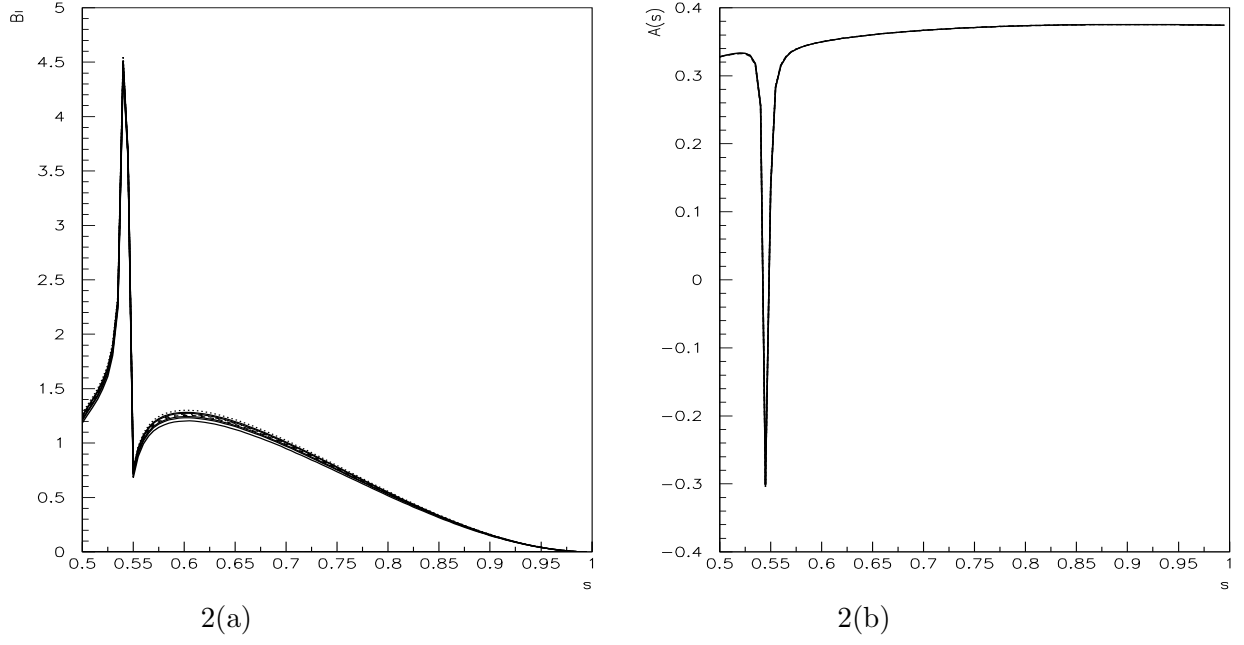\tag{16}
$$

Numerical results are shown in figs. 2 and 3.

Figuer 2: (a) $Br(s)$ and (b) $A(s)$ of $B \to X_s \tau^+ \tau^-$ with massof t' when $V_{t's}^* V_{t'b}$ is positive.
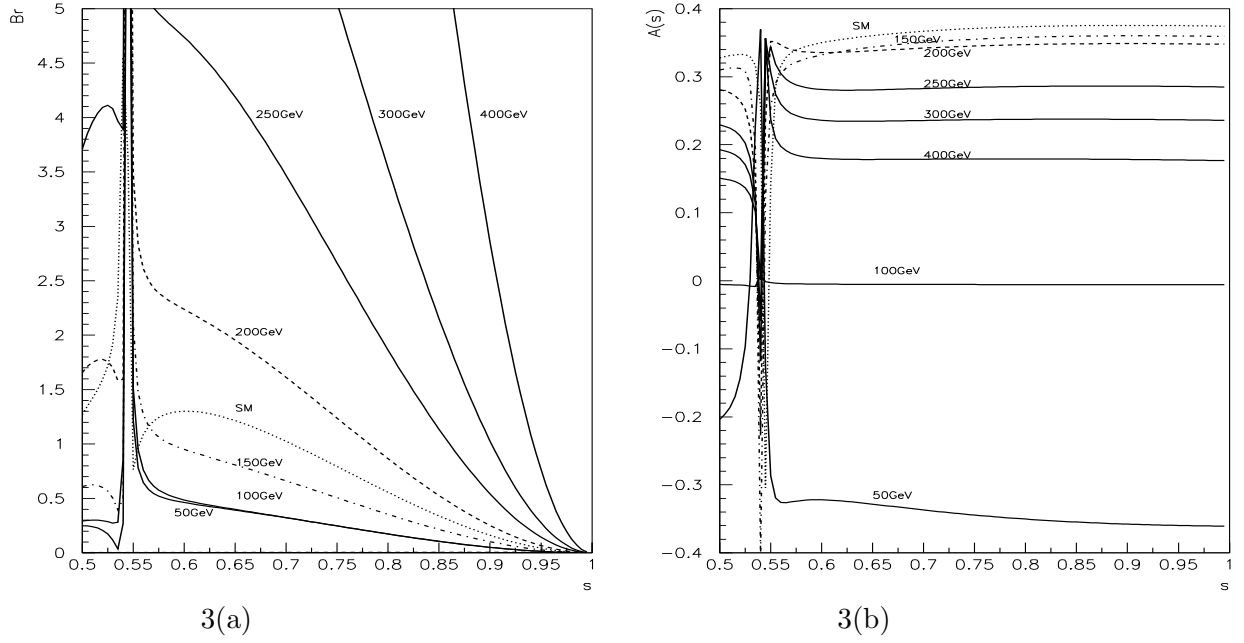

Figuer 3: same when $V_{t's}^* V_{t'b}$ is negative.

The invariant mass distribution and the forward-backward asymmetry in the case of $V_{t's}^* V_{t'b}^{(-)}$ are shown in the figs.2a and 2b respectively. The five curves, which are corresponding to $m_{t'}$=50Gev, 100Gev, 150Gev, 200Gev respectively in four fourth generation model and the SM one, almost overlap together. That is, the results in SM4 are the same as that in SM. In this case, it does not show the new effects of t'. We cannot obtain the information of existence of the fourth generation from B decays, although we cannot exclude them either. This is because, from tab. 2, the values of $V_{t's}^* V_{t'b}^{(-)}$ are positive. They are of order 10^{-3}. The values of $V_{ts}^* V_{tb}$ are about ten times larger than them ($V_{ts}^* = 0.038$, $V_{tb} = 0.9995$, see ref. [26]). Furthermore, $C_7^{(4)\mathrm{eff}}(\mu_b)$, $C_9^{(4)}(\mu_b)$, $C_{10}^{(4)}(\mu_b)$ are approximately equal to the ones in SM. Thus the contributions of t' to $C_7^{\mathrm{eff}}(\mu_b)$, $C_9(\mu_b)$, $C_{10}(\mu_b)$ in eqs. (5), (11), (12) are negligible .

In the other case, when the values of $V_{t's}^* V_{t'b}^{(+)}$ are negative, the numerical results are very different from that of SM. This can be clearly seen from figs. 3a and 3b. From fig. 3a, it is found that the deviations from SM depend on the mass of t'. The enhancement of the invariant mass distribution increases with increasing of t' quark mass. It gets to the most largest deviation, about 100% enhancement compared to SM, when t' mass is 200GeV. When the mass is taken to be 150GeV, the invariant mass distribution is about 30% low than that in SM. If the mass is taken to be under 100GeV, it is about half of the SM one. Even we take the mass of t' as a fitting value (between 150GeV and 200GeV), the shape of the curve is very different from the SM one. So, in this case, the fourth generation effects are shown clearly. The backward-forward asymmetry is also different from SM and show its own interesting things. From fig.3b, one sees that the curves are much lower than the SM one when the mass of t' is taken to be under 100GeV. The backward-forward asymmetry is almost vanishing as t' mass is equal to 100GeV. When t' mass is 50GeV, it is completely opposite to the SM one. But when we take the t' mass from 100GeV to 150GeV, the deviation from SM becomes smaller and smaller. Especially, when t' mass is near 150GeV, the curve is very like the SM one. But when we take t' mass upper 150GeV, the backward-forward asymmetry deviates from that of SM again. The deviation increases with the mass. The reason is that $V_{t's}^* V_{t'b}^{(+)}$ is 2-3 times larger than $V_{ts}^* V_{tb}$ so that the second term of right of the eqs. (5), (11), (12) becomes important and it deponds on the t' mass strongly. Thus, the effect of the fourth generation is significant. In this case, the decay of $B \to X_s l^+ l^-$ could be a good probe to the existence of the fourth generation.

4 Conclusion

In this note, we have studied the rare B decay process $B \to X_s l^+ l^-$ as well as the decay $B \to X_s \gamma$ in SM4. We obtained two solutions of the fourth generation CKM factor $V_{t's}^* \cdot V_{t'b}$ from the experimental data of $B \to X_s \gamma$. We have used the two solutions to calculate the contributions of the fourth generation quark to Wilson coefficients of $B \to X_s l^+ l^-$. We have also calculated the branching ratio and the backward-forward asymmetry of the decay $B \to X_s l^+ l^-$ in the two cases. It is found that the new results are quite different from that of SM when the value of the fourth generation CKM factor is negative, almost the same when the value is positive. Therefore, the B meson decays could provide a possible way to probe the existence of the forth generation if the fourth generation CKM factor $V_{t's}^* \cdot V_{t'b}$ is negative.

Acknowledgments

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